CHAPTER 6

TRIBOLOGICAL CHARACTERISTICS OF CS CAST A356-Mg_2Si-TiB_2 HYBRID COMPOSITE

6.1 INTRODUCTION

This chapter deals the investigation of tribological behaviour of CS cast A356-10Mg_2Si-xTiB_2 in dry sliding condition. Tribological characteristics have been studied using various input variables such as sliding distance, applied load, sliding velocity and wt.% of TiB_2 particles. Worn surfaces have been examined under SEM with EDS and AFM. Debris analysis has also been done by SEM. Obtained results have been correlated with the worn surface topography.

6.2 WEAR & FRICTION BEHAVIOR UNDER DRY SLIDING

6.2.1 Influence of Sliding Distance

Figure 6.1 (a-d) presents the influence of sliding distance on wear volume of cooling slope (CS) cast A356 alloy and A356-10Mg_2Si composite and A356-10Mg_2Si-xTiB_2 hybrid composites with different TiB_2 content at different applied loads of 10 N to 40 N. Wear volume steadily increases with increasing sliding distance, especially at lower applied load. With increase of the applied load, wear volume linearly increases up to certain sliding distance (3000 m) showing steady state wear. Beyond that wear volume increases slightly faster with increasing sliding distance. However, wear volume reduces with increasing TiB_2 weight percentage owing to grain refinement and higher weight fraction of reinforcement. The composite cast through the cooling slope technique exhibits better wear resistance.

The increased wear resistance of CS cast composites is due to various factors, such as particle size reduction of primary Mg_2Si phase and elimination of sharp corners which can be crack initiation sites, secondly the eutectic Mg_2Si and Si phase shape was changed to spherical shape. The insitu generated reinforcement particles are well bonded with matrix and have clean interface which maintains their integrity during sliding wear. The clean interface and strong bonding between reinforcement and matrix prevent particles from detaching out of the matrix, resulting in better wear resistance. Fig. 6.2 depicts the wear rate of CS cast composites with increasing sliding distance at constant applied load of 30 N. Wear rate of hybrid composites decreases up to 3000 m sliding distance, after that it stabilise showing steady sate wear owing to higher load bearing capacity of hybrid composites.

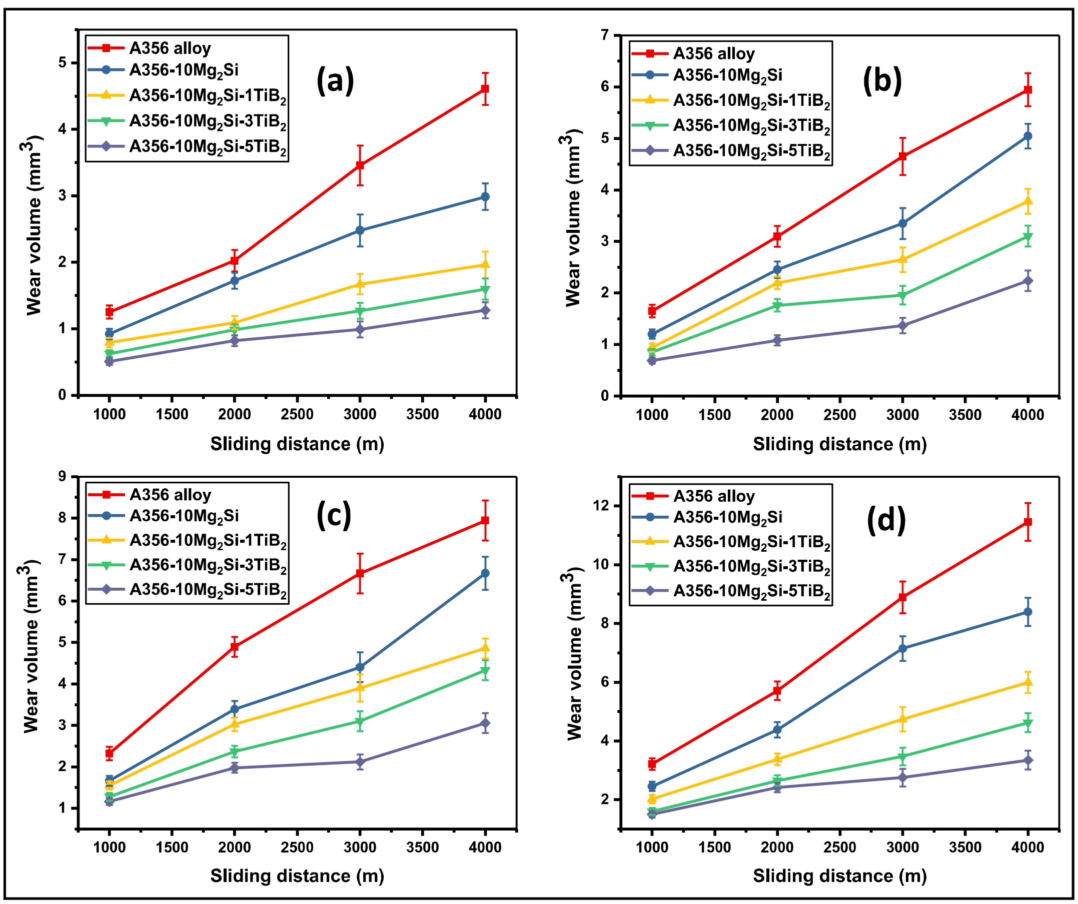

Fig. 6.1 Influence of sliding distance on wear volume at different applied loads **(a)** 10 N **(b)** 20 N **(c)** 30 N **(d)** 40 N

Figure 6.3 (a-d) depicts the fluctuation of the COF with sliding distance at various applied loads (10 to 40 N) and fixed sliding velocity (1.5 m/s). The graph demonstrates that the COF increases consistently for the composites up to 3000m sliding distance, beyond that it starts decreasing. The increase that is seen in the COF with increasing sliding distance can be due to an increase in the temperature of mating surfaces, resulting in higher frictional force. Furthermore, the COF decreases from matrix alloy to hybrid composites as TiB_2 content increases in given sliding conditions. It's likely that adding more fine reinforcement reduces the fraction of matrix surface that comes into contact with the counterface. This reduces the adherence of aluminium to the counter surface, lowering the temperature rise caused by frictional heat.

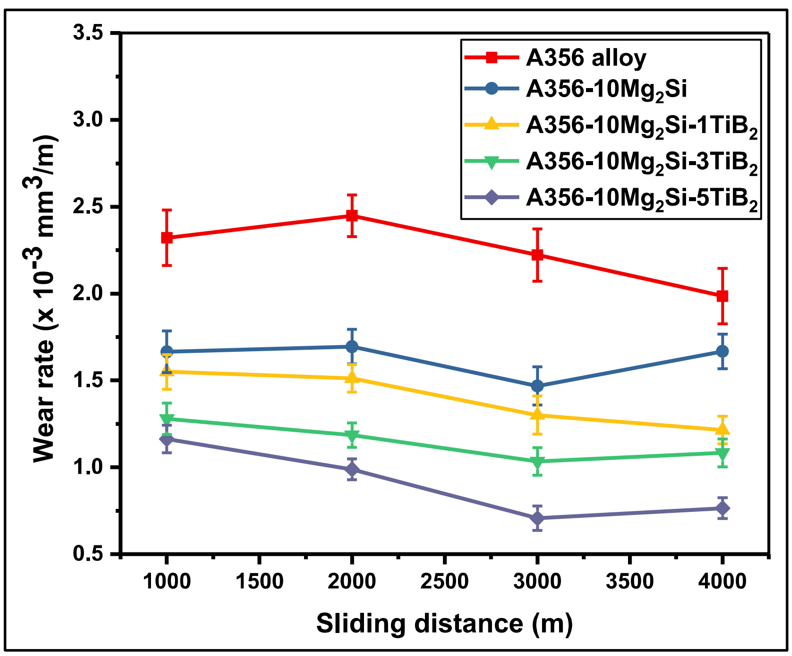

Fig. 6.2 Influence of sliding distance on wear rate at applied loads 30 N

Figures 6.4 (a-d) displays the SEM micrograph of worn surfaces of CS cast hybrid composite $A356-10Mg_2Si-3TiB_2$ with changing sliding distances ranging from 1000 to 4000 m. The worn surfaces have parallel grooves in the sliding direction caused by ploughing action by asperities on the hard counter face. The figure indicates that wear increases with the sliding distance but after the 3000 m of sliding distance severity of wear increases with deep ploughing and delamination. Figure 6.5 (a-d) depicts the 3D AFM image of worn surfaces of $A356-10Mg_2Si-xTiB_2$ hybrid composite with changing sliding distance from 1000 m to 4000 m. It indicates that average peak and valley of worn surface increases from 1.6 µm to 3.5 µm with the sliding distance. The SEM image of worn surfaces and surface roughness found to be in similar trends with the result of wear rate.

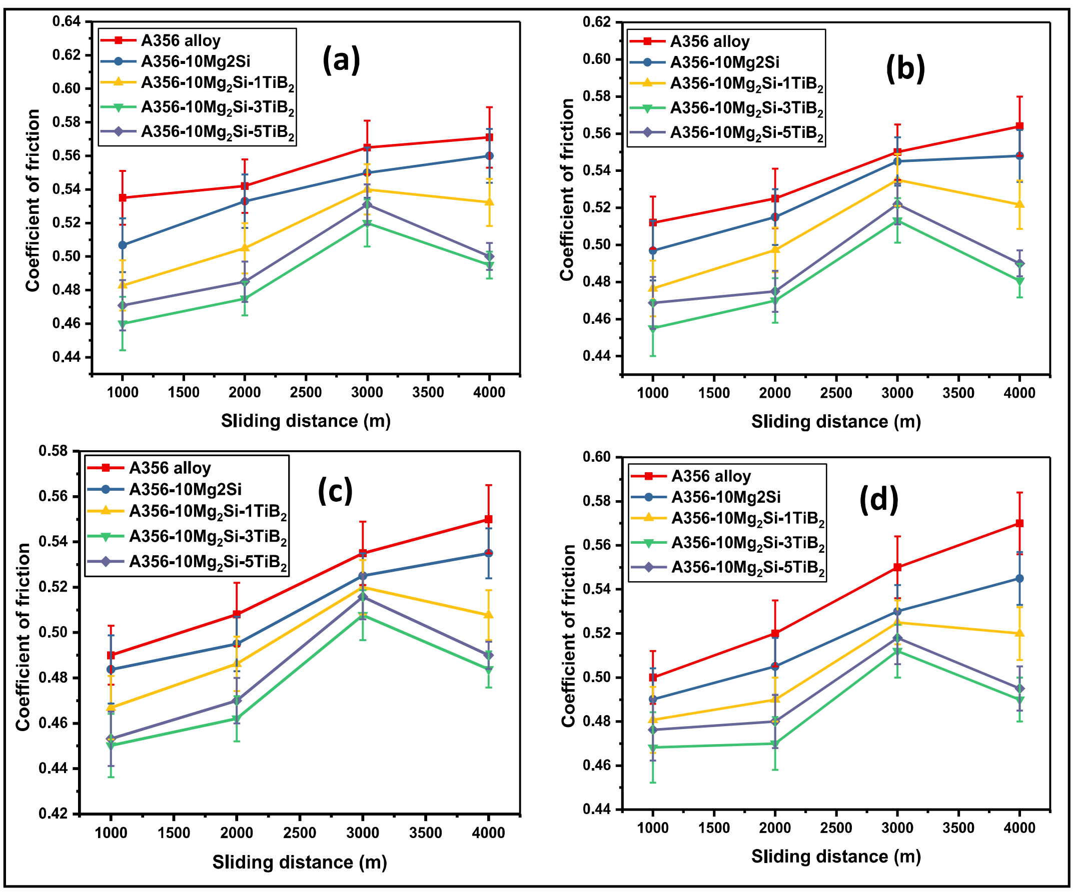

Fig. 6.3 Influence of sliding distance on COF at different applied loads (a) 10 N (b) 20 N (c) 30 N (d) 40 N

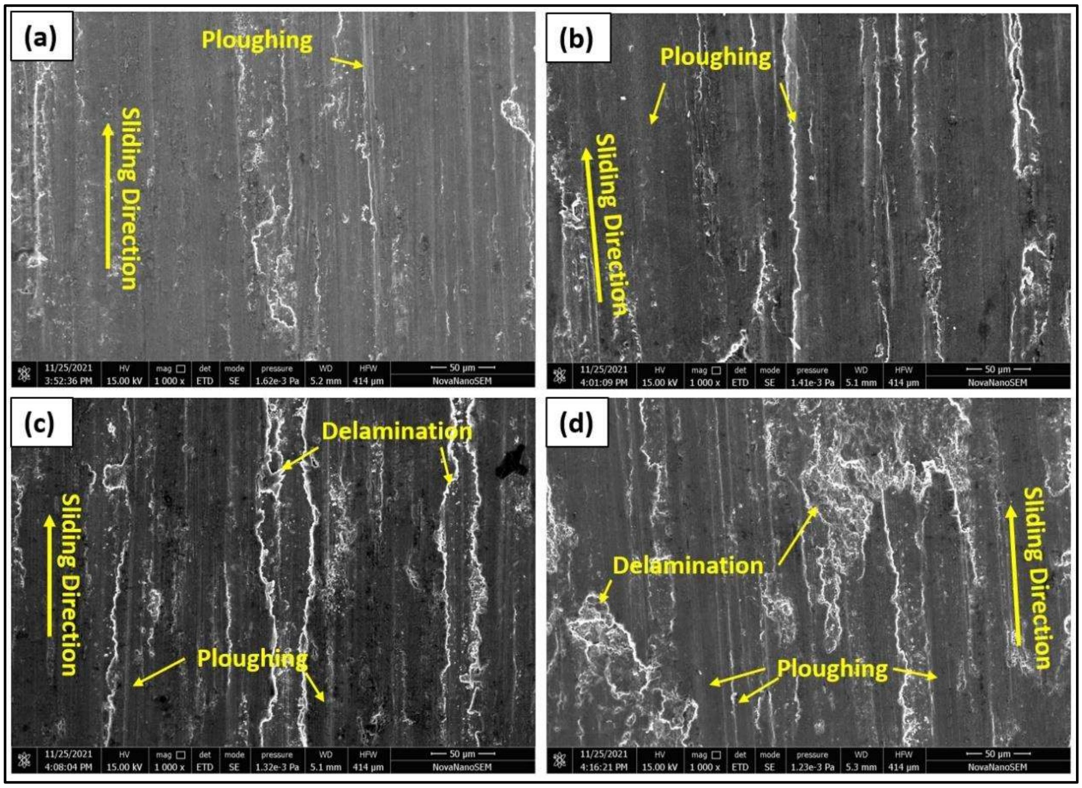

Fig. 6.4 SEM images of worn surface of A356-10Mg_2Si-3TiB_2 hybrid composite at 30 N load and sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m

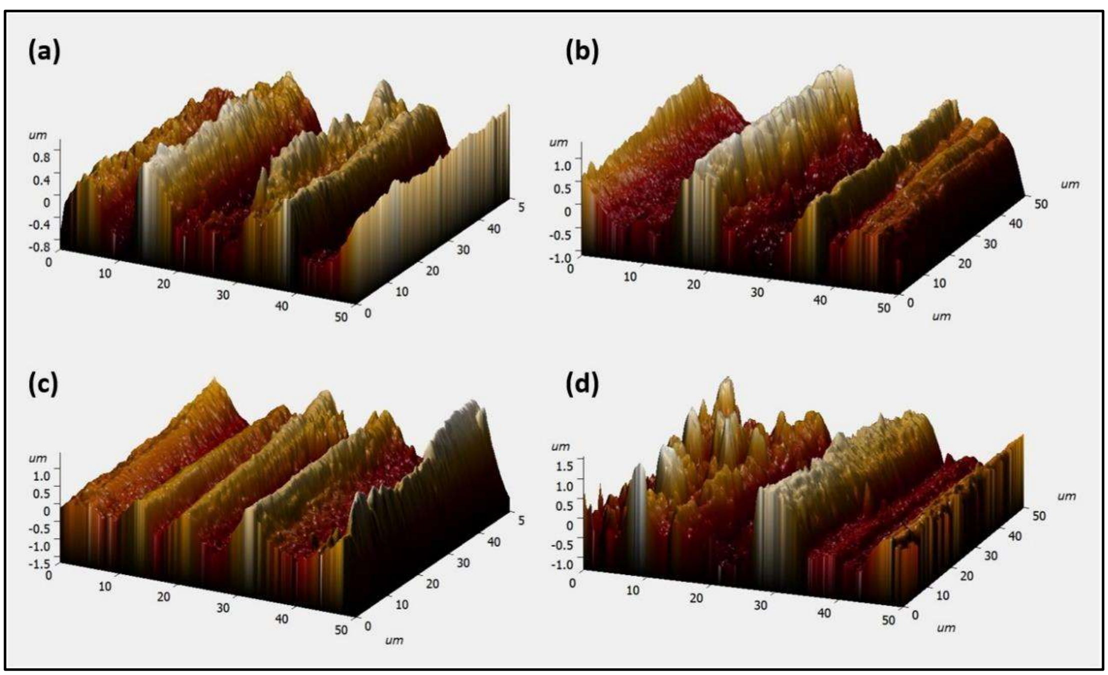

Fig. 6.5 AFM image of A356-10Mg_2Si-3TiB_2 hybrid composite at 30 N load and sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m

6.2.2 Influence of Load

Figures 6.6 and 6.7 show the effect of load on wear rate and specific wear rate of hybrid composites at various sliding distance 1000 m - 4000 m. The graph readily reveals that the wear rate of all CS cast A356 alloys and composites increases with increasing load. The wear rate grows slowly up to around 20 N of applied load, indicating steady state wear, and above 20 N loads, wear rate changes from moderate to severe wear results in a substantial increase in wear rates. However, at higher sliding distance wear rate linearly increases up to 30 N and beyond that steady state wear regime achieved. The reduced wear rate of composites containing 3 wt.% or 5 wt.% TiB_2 particles can be owing to high weight fraction of reinforcing phase. Up to 20 N of applied load, the specific wear rate of CS cast composites reduces; after that, it stabilises or tends to decrease with increasing load as presented in Fig 6.7.

Figure 6.8 (a-d) show the influence of applied loads on COF of composites at various sliding distance (1000m-4000m). The figure indicates that COF initially decreases as load increases up to 30 N because an oxide layer forms on the pin surface, providing a smooth surface. However, as load goes above 30 N, the oxide layer breaks and reinforcements phase comes into direct contact with the counter face, increasing the COF.

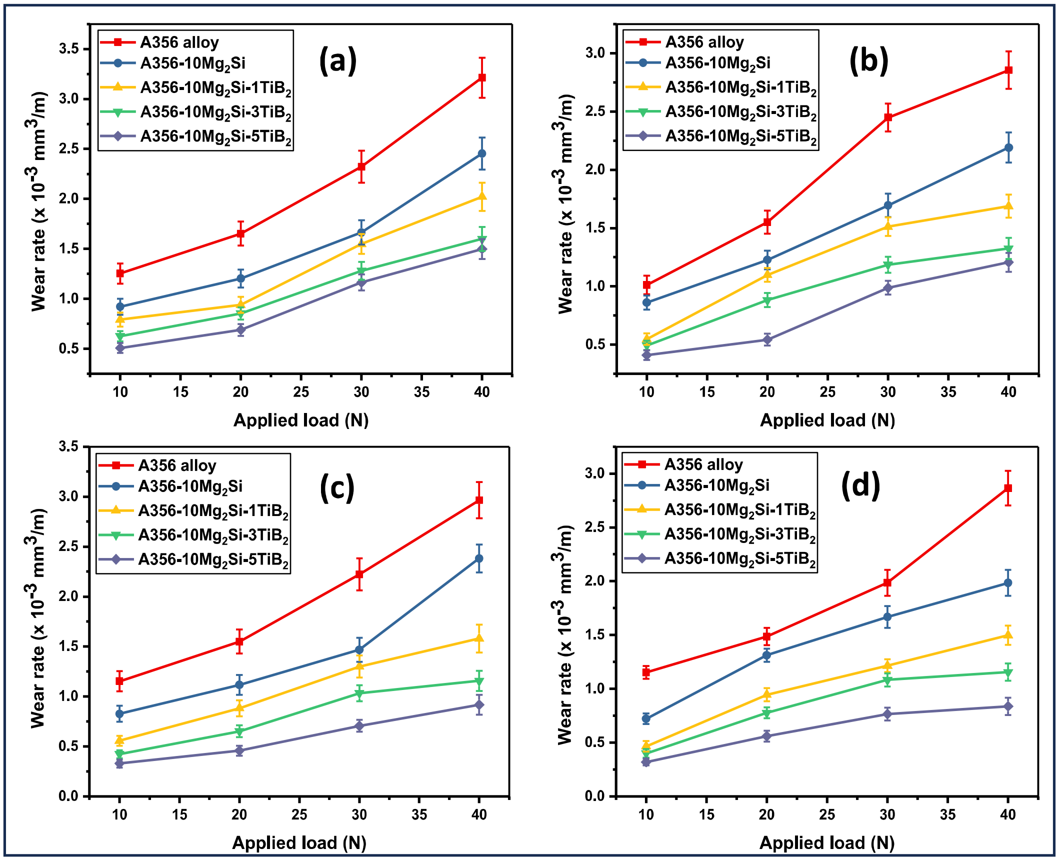

Fig. 6.6 Influence of applied load on wear rate at sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000m

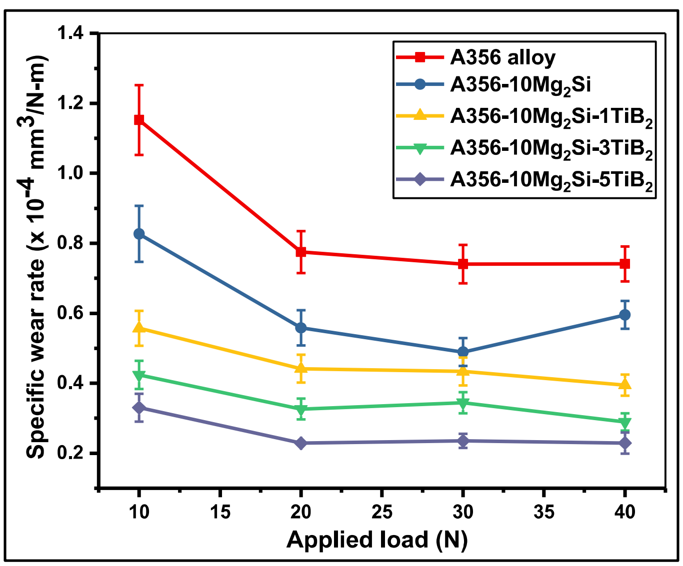

Fig. 6.7 Influence of applied load on specific wear rate at sliding distance of 3000m

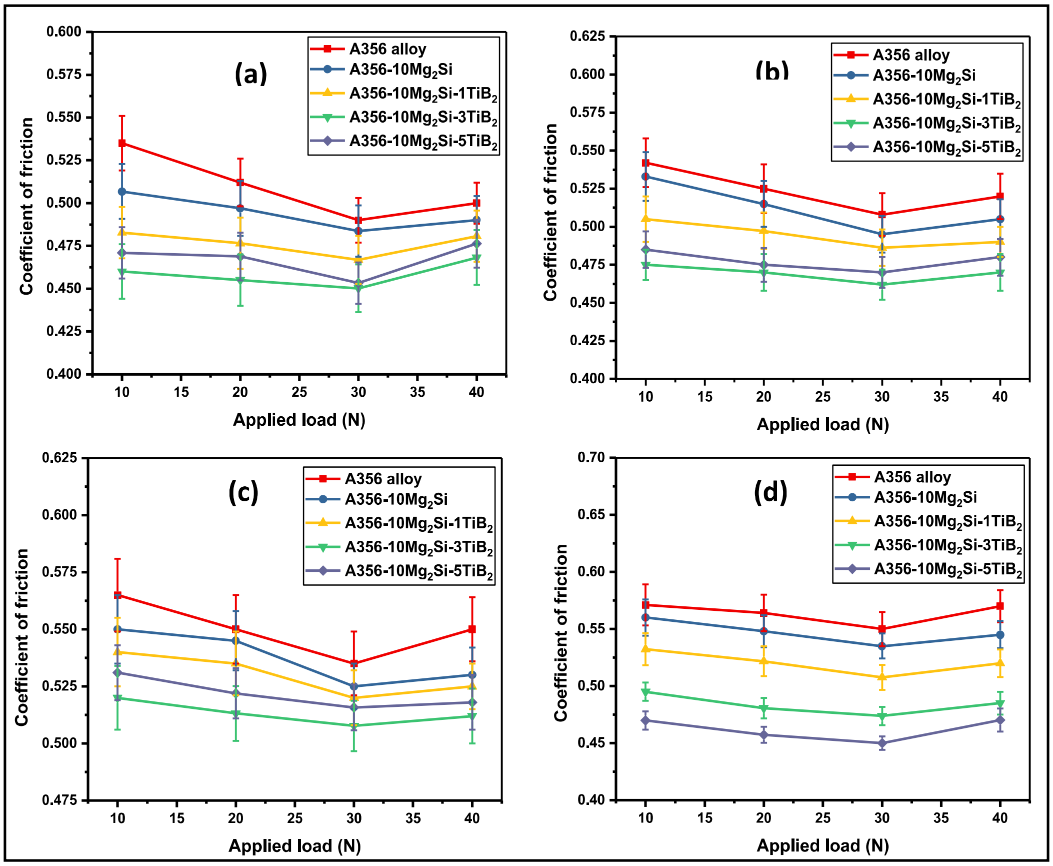

Fig. 6.8 Influence of applied load on COF at sliding distance (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m

Figures 6.9 (a-d) shows the worn surfaces of hybrid composite A356-10Mg_2Si-3TiB_2 at various loads 10 to 40 N. Fig. 6.9 (a) exhibits relatively smoother surface with shallow ploughing showing mild wear regime. At low applied loads, asperities on the counter surface and hard particles between contact surfaces causes ploughing or cutting of softer matrix. Consequently, tiny fragments of material are removed which lead to abrasive wear. As the applied load increases, deeper grooves are generated by harder counter face asperities penetrating deeper and delamination takes place. The worn surface is substantially damaged exhibiting deep grooves and large delamination suggesting a severe wear at higher applied load of 40 N as depicted in Fig. 6.9 (d). Fig. 6.10 (a-b) presents the SEM image of worn surfaces and EDS spectra of the whole area of micrograph of CS cast A356-10Mg_2Si-3TiB_2 hybrid composite. In addition to Al, Si, Mg, Ti, and B, the worn surface also includes Fe and O, as shown in the EDS spectra, which supports the formation of an oxide layer and a mechanically mixed layer (MML). The wear rate and COF are reduced by the presence of an oxide layer on the pin surface and MML between the mating surfaces. The AFM image of worn surfaces are presented in Fig. 6.11 (a-d) to examine the surface roughness of the hybrid composite under various loads. We can see that, when the applied load increases from 10 N to 40 N, the average peak height to valley depth increases from 1.6 µm to 3.5 µm.

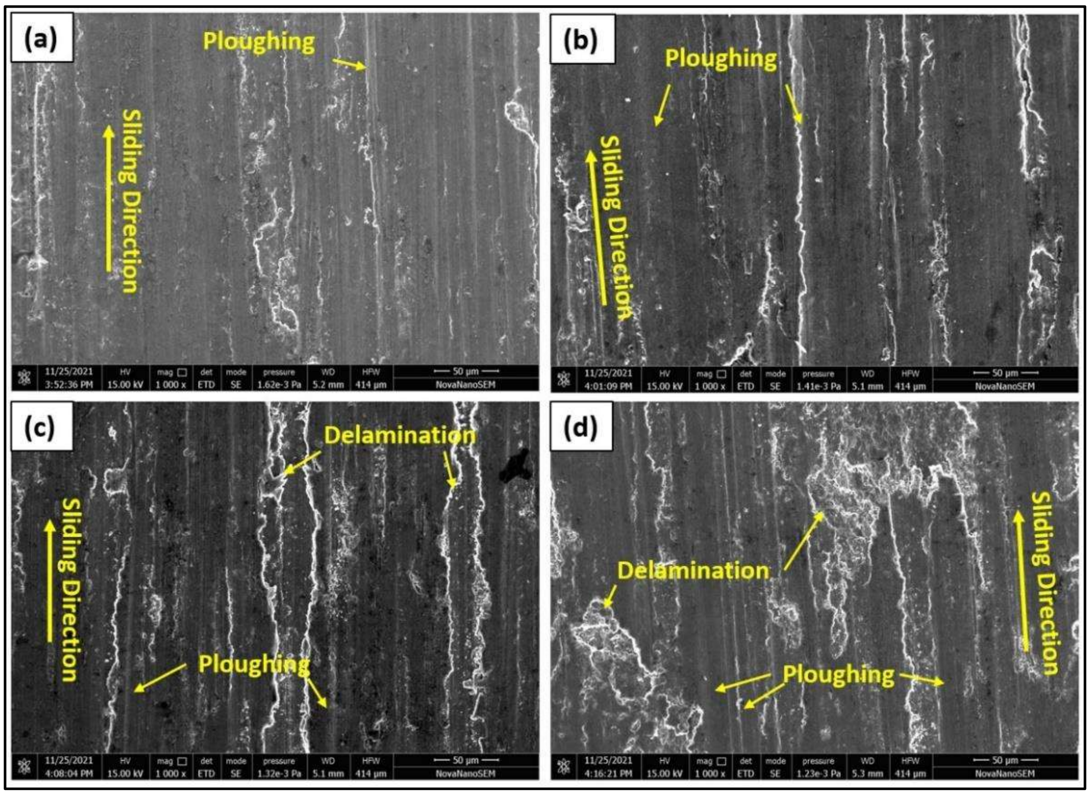

Fig. 6.9 SEM images of worn surface of $A356-10Mg_2Si-3TiB_2$ hybrid composite at 3000 m of sliding distance and applied load of (a) 10 N (b) 20 N (c) 30 N (d) 40 N

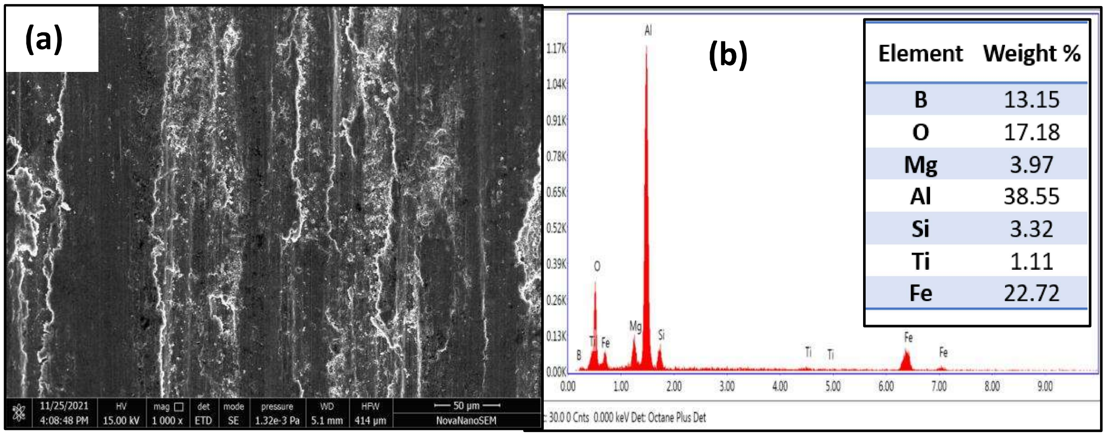

Fig. 6.10 (a) SEM micrograph of worn surface A356-10Mg_2Si-3TiB_2 hybrid composite at applied load 30 N, (b) EDS spectrum of whole area of SEM micrograph

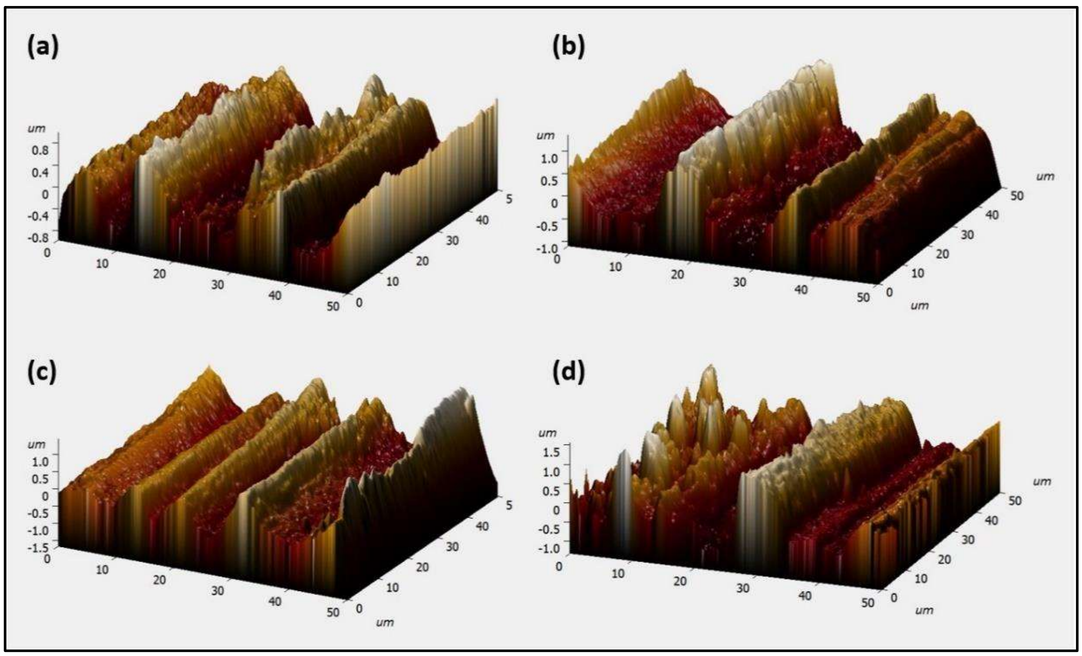

Fig. 6.11 AFM image of A356-10Mg_2Si-3TiB_2 hybrid composite at 3000 m of sliding distance and applied load of (a) 10 N (b) 20 N (c) 30 N (d) 40 N

6.2.3 Influence of Sliding Velocity

Figure 6.12 (a-d) displays the effect of sliding velocity on the wear rate of composites at various applied loads varying from 10 to 40 N. For all compositions, the wear rate increases as the sliding velocity increases. However, wear rate of the base alloy increases rapidly with increasing sliding velocity. This might be attributed to rise in pin surface temperature that softens the matrix phase and hence, substantially increase in wear rate at higher sliding velocity takes place. Hybrid composites show a substantial reduction in wear rate at all sliding velocity compared with the base alloy specially at high sliding velocity. The enhanced wear resistance of hybrid composites may be associated with several aspects such as the improved hardness and strength and improved thermal stability and hot hardness by incorporating TiB_2 phase in the composite.

Figure 6.13 (a-d) displays that the influence of sliding velocity on COF of alloy and composites at applied loads of 10-40 N. The graph clearly reveals that COF decreases with increasing sliding velocity. This occurs due to faster oxidation of surface due to frictional heating, reduced adhesion and iron oxide in the MML, which decreases the COF at high sliding velocity. However, COF for base alloy starts increasing due to the increase of adhesion of matrix phase with counter face at high applied load and sliding velocity.

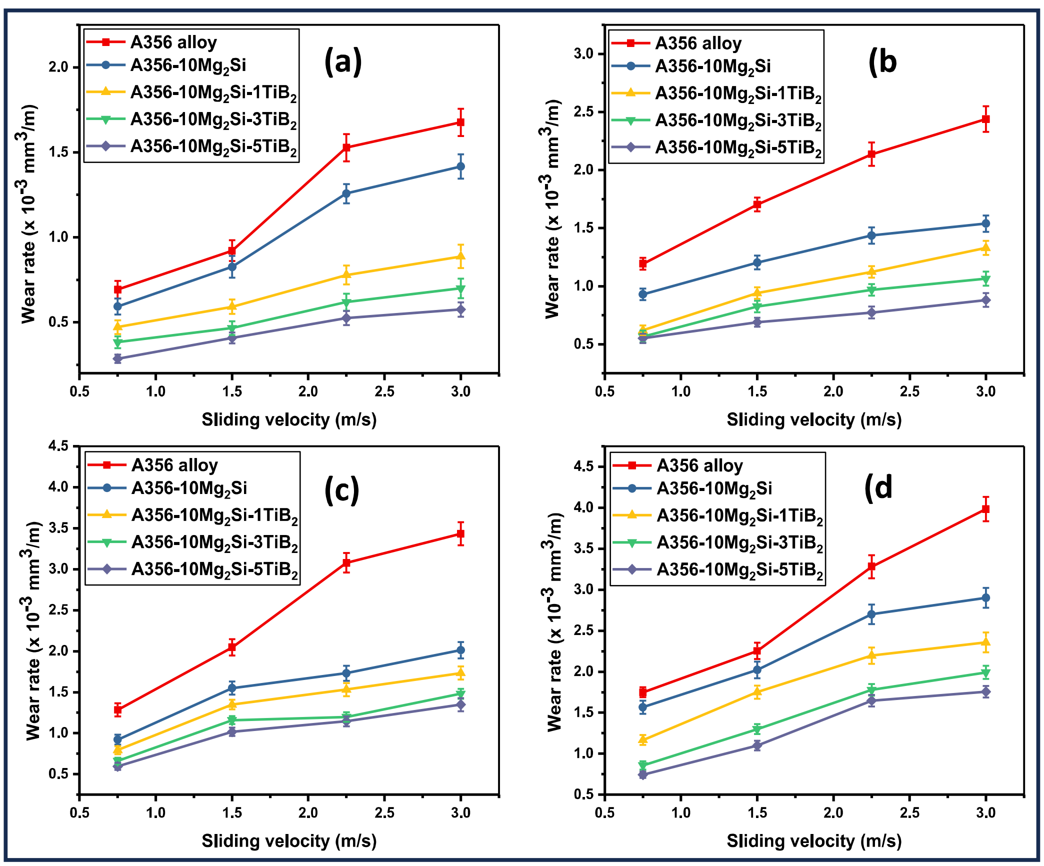

Fig. 6.12 Influence of sliding velocity on wear rate at sliding velocity of 1000 m and different applied loads (a) 10 N (b) 20 N (c) 30 N (d) 40 N

Figure 6.14 (a-d) presents worn surfaces of hybrid composite A356-10Mg_2Si-3TiB_2 at various sliding velocity 0.75 m/s to 3 m/s and 30N of applied load. Fig. 6.14 (a) displays the smooth surface with shallow ploughing and very little delamination attributed to low frictional heating at 0.75 m/s sliding velocity. As illustrated in Fig. 6.14 (b-d), the depth of ploughing and delamination increases as the sliding velocity increases. Fig. 6.14 (d) shows the deep wear groove and large delamination owing to high frictional heating at higher sliding velocity. This heating removes the protective oxide layer from the pin surface resulting in higher wear rate. In order to further analyse the worn surfaces,

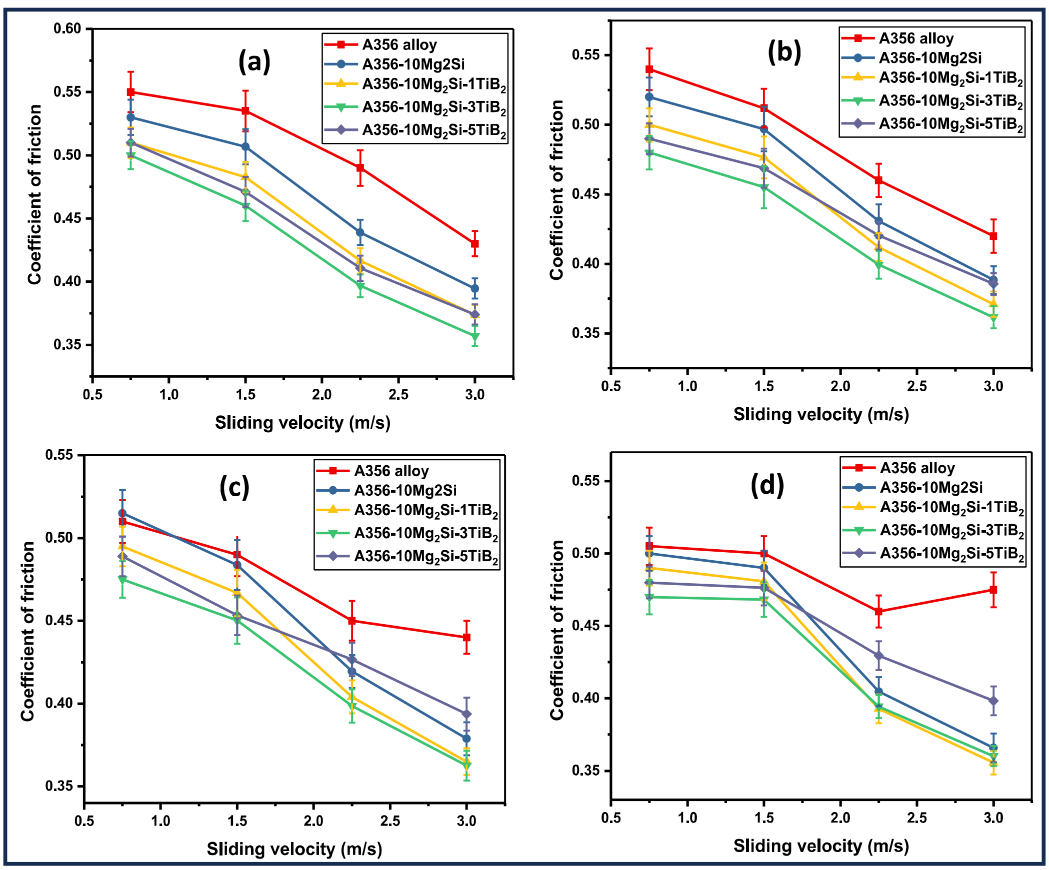

Fig. 6.13 Influence of sliding distance on COF at sliding distance of 1000 m and different applied loads (a) 10 N (b) 20 N (c) 30 N (d) 40 N

AFM was used to determine the unevenness and surface roughness. Fig. 6.15 (a-d) displays the 3D AFM images of worn surface of A356-10Mg_2Si-3TiB_2 composite at different sliding velocity 0.75 m/s to 3 m/s. These images clearly show that variation of surface roughness from 1.6 µm to 3.5 µm valley depth to peak height. 3D surface topography reveals shallow ploughing at 0.75m/s to deep wear groove and large delamination at sliding velocity of 3 m/s.

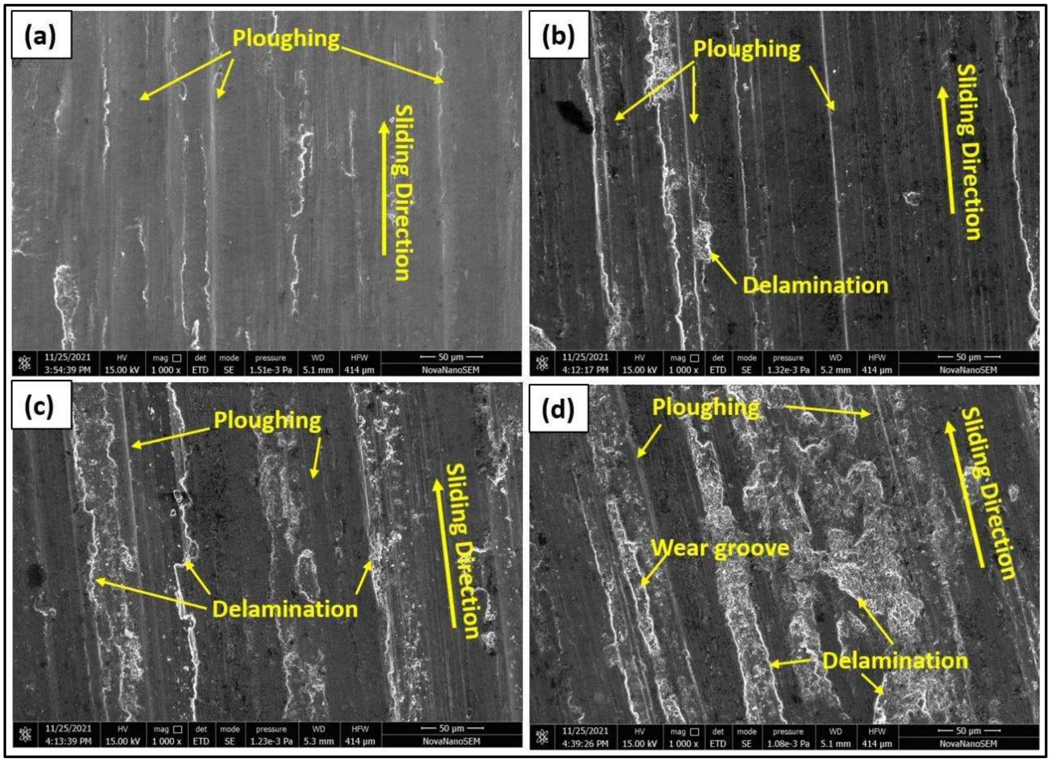

Fig. 6.14 SEM image of worn surface of $A356-10Mg_2Si-3TiB_2$ hybrid composite at 30 N load and 1000 m of sliding distance and sliding velocity of (a) 0.75 m/s (b) 1.5 m/s (c) 2.25 m/s (d) 3 m/s

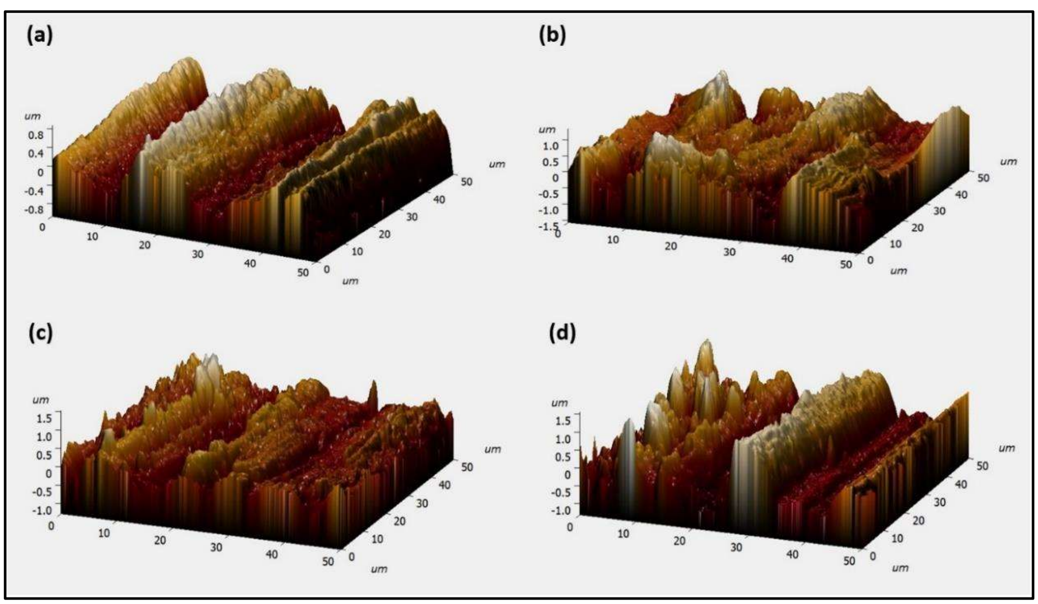

Fig. 6.15 AFM image of $A356-10Mg_2Si-3TiB_2$ hybrid composite at 30 N load and 1000 m of sliding distance and sliding velocity of (a) 0.75 m/s (b) 1.5 m/s (c) 2.25 m/s (d) 3 m/s

6.2.4 Influence of TiB_2 Amount

The effect of wt.% of TiB_2 particles on wear rate and COF of the composites at different sliding distance (1000-4000 m) and fixed 30 N load and 1.5 m/s sliding speed is illustrated in Fig.6.16 and 6.17 respectively. The figure demonstrates that with increase in the TiB_2 concentration in the composite, the wear rate of the composites decreases. This result can be attributable to a number of factors that contribute to an improvement in wear behaviour. The improvement in bulk hardness is mostly attributed to grain refinement, strong interfacial bonding and higher dislocation density. Moreover, increase of reinforcing phase reduces the metal-to-metal contact during sliding wear protects the matrix phase and decreases the wear rate. Addition of TiB_2 particles in $A356-Mg_2Si$ composite increases the dislocation density around the Mg_2Si phase & improves hardness and strength of hybrid composites.

Furthermore, development of oxide layer on pin surface also hinders the metal removal from the surface. COF of composites decreases as the amount of TiB_2 particles goes up to 3wt.% in $A356-Mg_2Si$ composite due to the lower surface contact. However, further increase of TiB_2 content in composite quantity of the particles in the MML increases, which slightly increases the COF owing to the abrasive action of the particles.

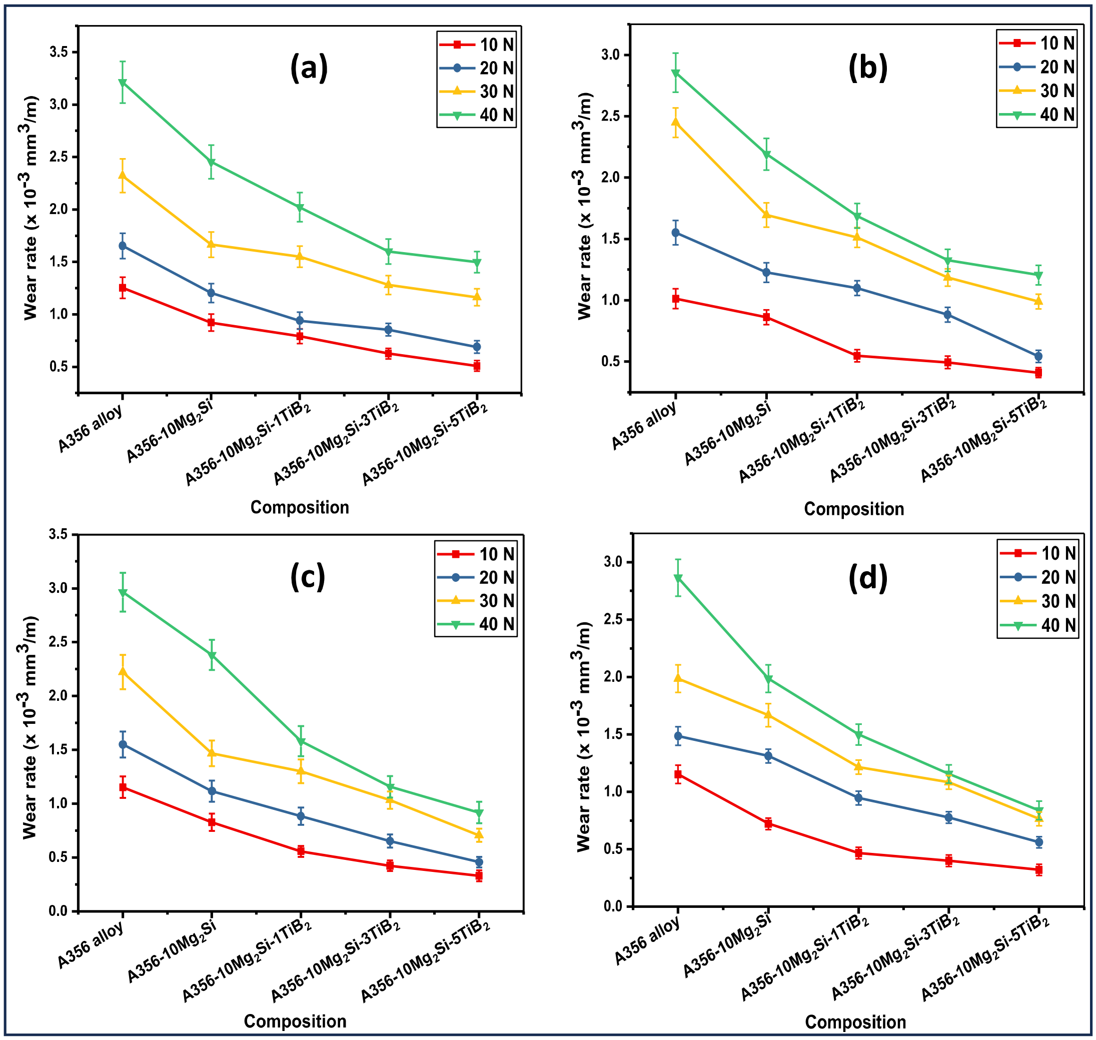

Fig. 6.16 Influence of TiB_2 content on wear rate at constant sliding velocity of 1.5 m/s and different sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m

Figure 6.18 shows the wear coefficient of matrix alloy and composites at 10N and 30N load and constant sliding distance of 3000 m. It was found that wear coefficient of alloy and composite decreases with increasing load. It was also noticed that with increasing TiB_2 content in the composites, wear coefficient decreases. This can be attributed that higher hardness of the composites than the alloy result in lower formation of wear particles. It may be due to the surface of composites is protected by the reinforcements during the plastic deformation.

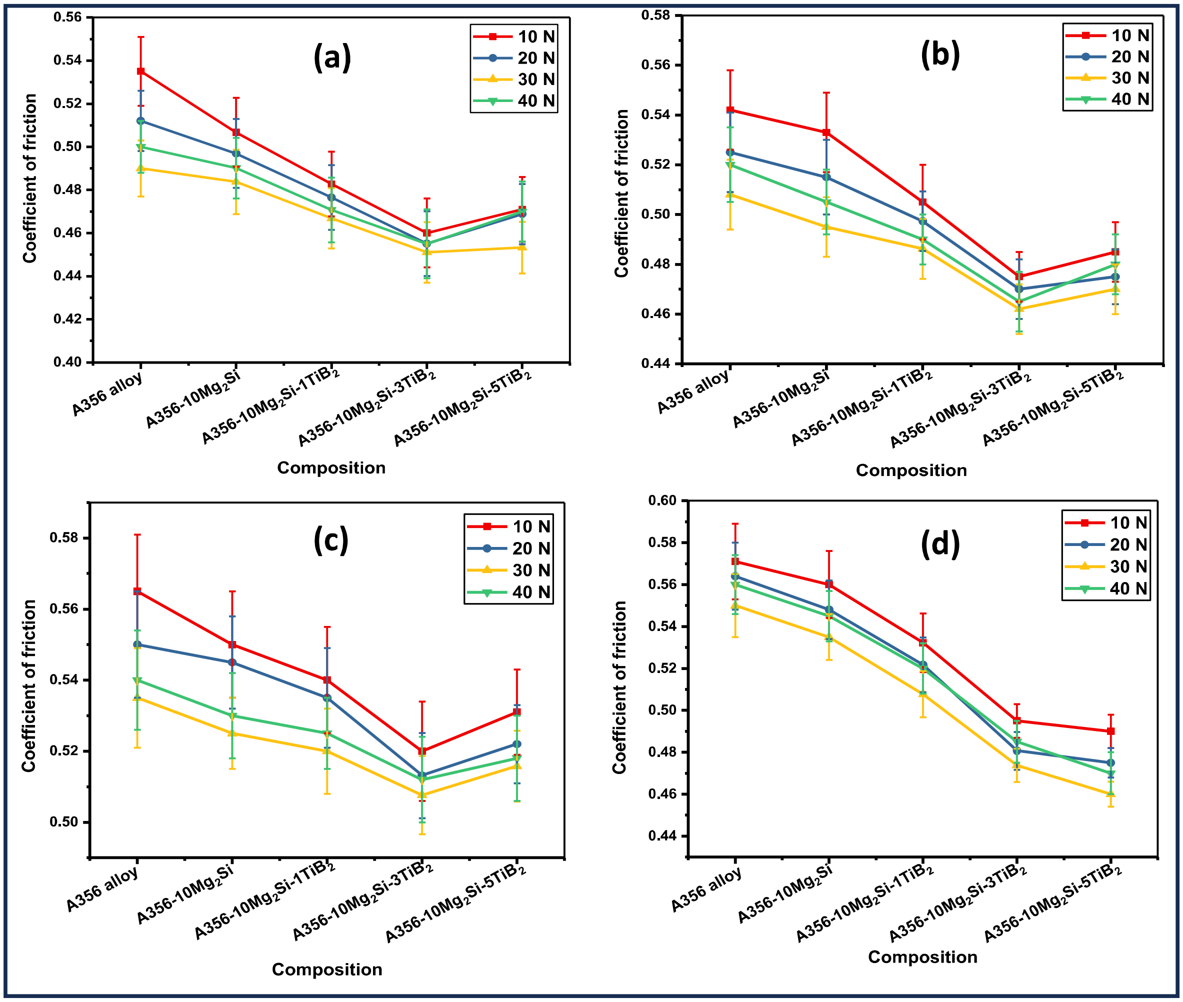

Fig. 6.17 Influence of TiB_2 content on COF at constant sliding velocity of 1.5 m/s and different sliding distance of (a) 1000 m (b) 2000 m (c) 3000 m (d) 4000 m

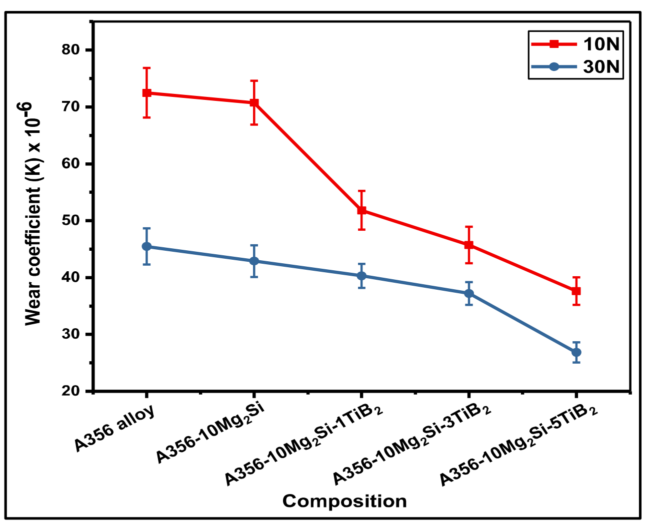

Fig. 6.18 Influence of TiB_2 content on wear coefficient at constant sliding distance

Figure 6.19 (a-e) presents SEM micrographs of worn surfaces of matrix alloy and A356-Mg_2Si-xTiB_2 hybrid composites with varying TiB_2 content at constant 30N load and 3000 m sliding distance. The worn surface of the matrix (Fig. 6.19 a) displays deep ploughing, significant delamination, and highly damaged regions, which might be caused by frictional heating of the surface and fragmentation of the oxide film. Whereas, worn surface of the composite displays shallow ploughing and reduced delamination as TiB_2 percentage in composite increases from 0 to 5 wt.%. Reduction in wear of hybrid composites is owing to grain refinement and improved hardness with increasing TiB_2 content in the composites.

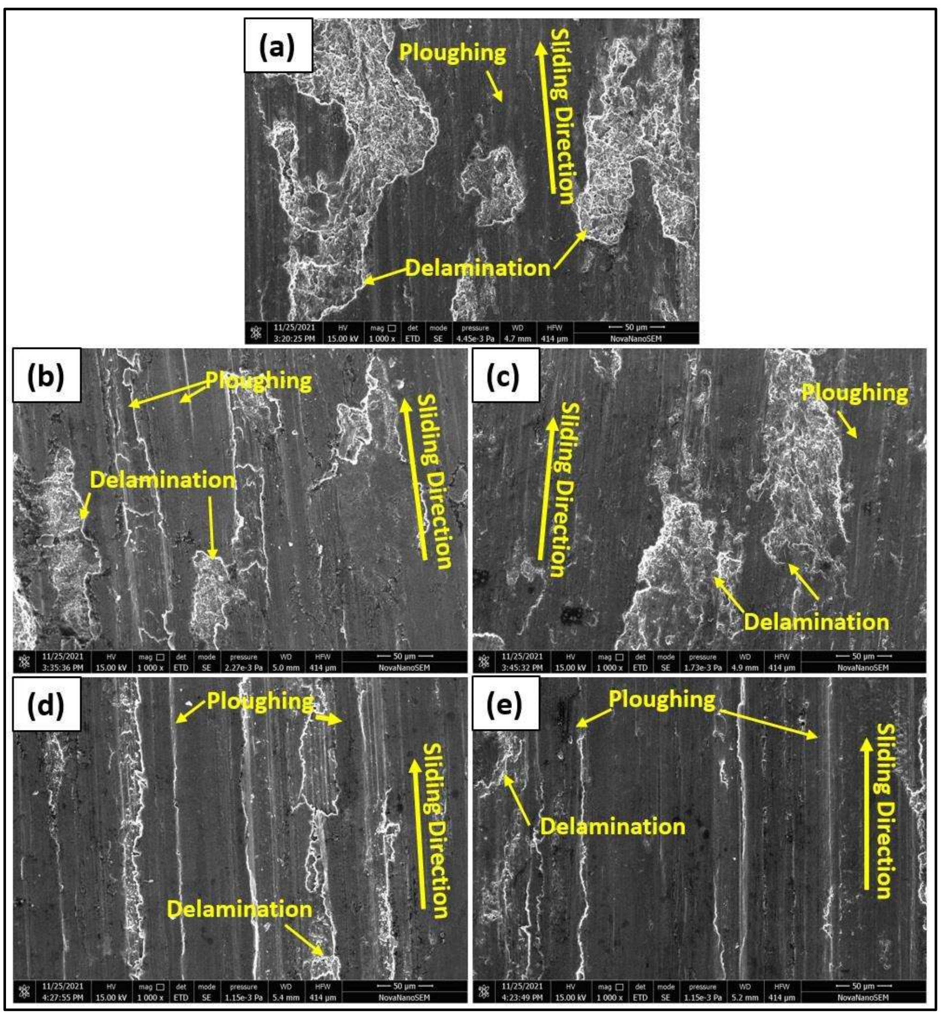

Fig. 6.19 SEM images of worn surface at 30 N load and 3000 m of sliding distance for (a) A356 alloy and A356-10Mg_2Si-xTiB_2 hybrid composite (b) x = 0 (c) x = 1 (d) x = 3 (e) x = 5

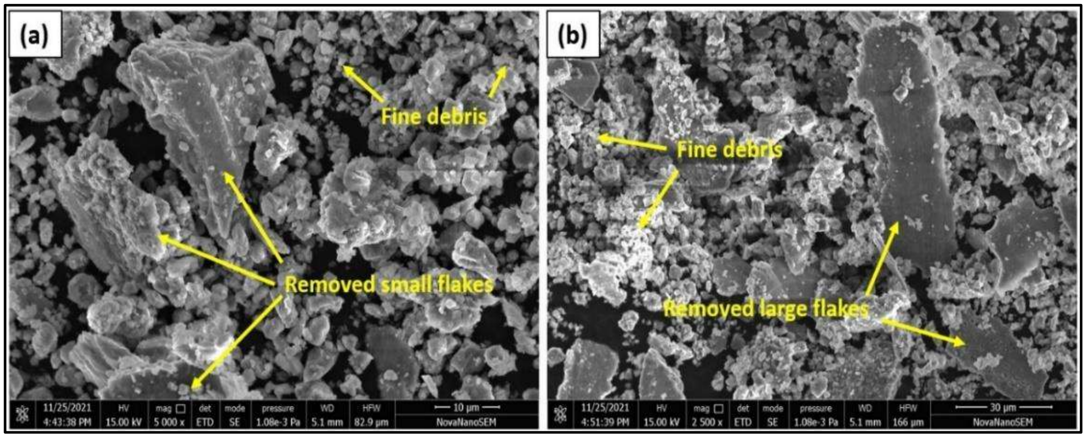

Fig. 6.20 Wear debris of A356-10Mg_2Si-3TiB_2 hybrid composite at applied load of (a) 20 N and (b) 40 N

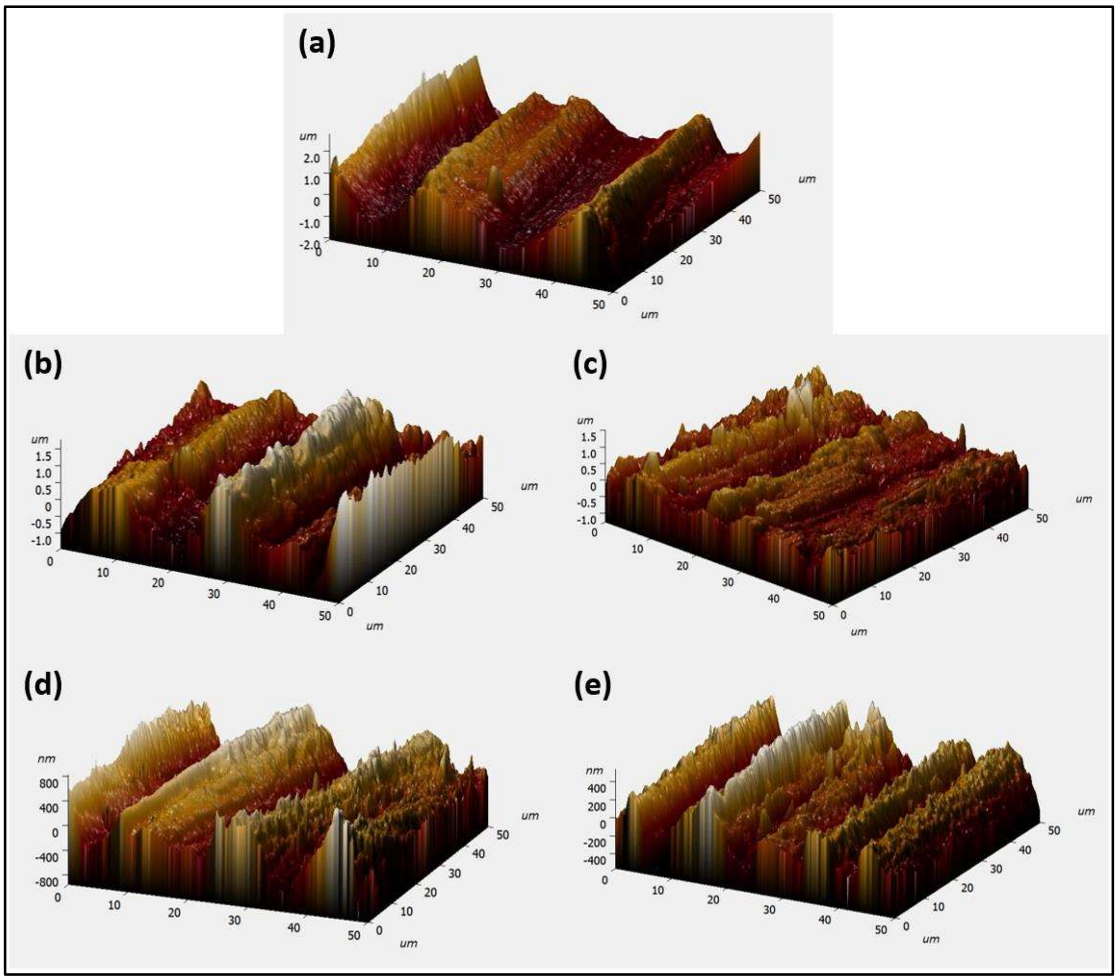

Fig. 6.21 AFM images of worn surface at 30 N load and 3000 m of sliding distance for (a) A356 alloy and A356-10Mg_2Si-xTiB_2 hybrid composite (b) x = 0 (c) x = 1 (d) x = 3 (e) x = 5

Figure 6.20 (a-b) presents the wear debris of $A356\text{-}Mg_2Si\text{-}xTiB_2$ hybrid composites at the load of 20 N and 40 N respectively. It can be clearly observed that small flakes along with fine wear debris formed at 20 N applied load due to wear is mostly dominated by abrasive wear. However, at 40 N applied load dominant wear mechanism is delamination in which due to abrasive wear debris is comprised of large flakes and fine particles.

Figure 6.21 (a-e) presents the 3D AFM micrograph of worn surfaces of matrix alloy and $A356\text{-}Mg_2Si\text{-}xTiB_2$ hybrid composites with varying amount of TiB_2 particles. It indicates that the surface unevenness and roughness decrease as the TiB_2 content increases in the hybrid composite. Average peak to valley height decreases from 4.0 µm to 0.8 µm as TiB_2 particle increases from 0 to 5 wt.%. The results obtained are consistent with the wear rate and worn surface observations.

6.3 COMPARATIVE STUDY OF TRIBOLOGICAL PROPERTIES OF STIR CAST AND CS CAST HYBRID COMPOSITES

Fig. 6.22 (a) and (b) display the comparison of wear rate and COF of composites fabricated through stir casting and CS casting route at fixed 30N load, 3000 m sliding distance and 1.5m/s sliding velocity. This indicates that the CS cast composites exhibit better wear properties owing to better refinement and distribution of Mg_2Si phase in the composites. Besides this, higher hardness of CS cast composites also significantly improves the wear resistance. COF of A356 alloy and single reinforced composite show higher value of COF compared to stir cast samples because of refinement of α-Al phase and even dispersion of Si phase, which enhances the strength of alloy. However, hybrid composites containing 3 and 5wt.% of TiB_2 particle showing lower COF than the stir cast samples due to higher hardness and strength.

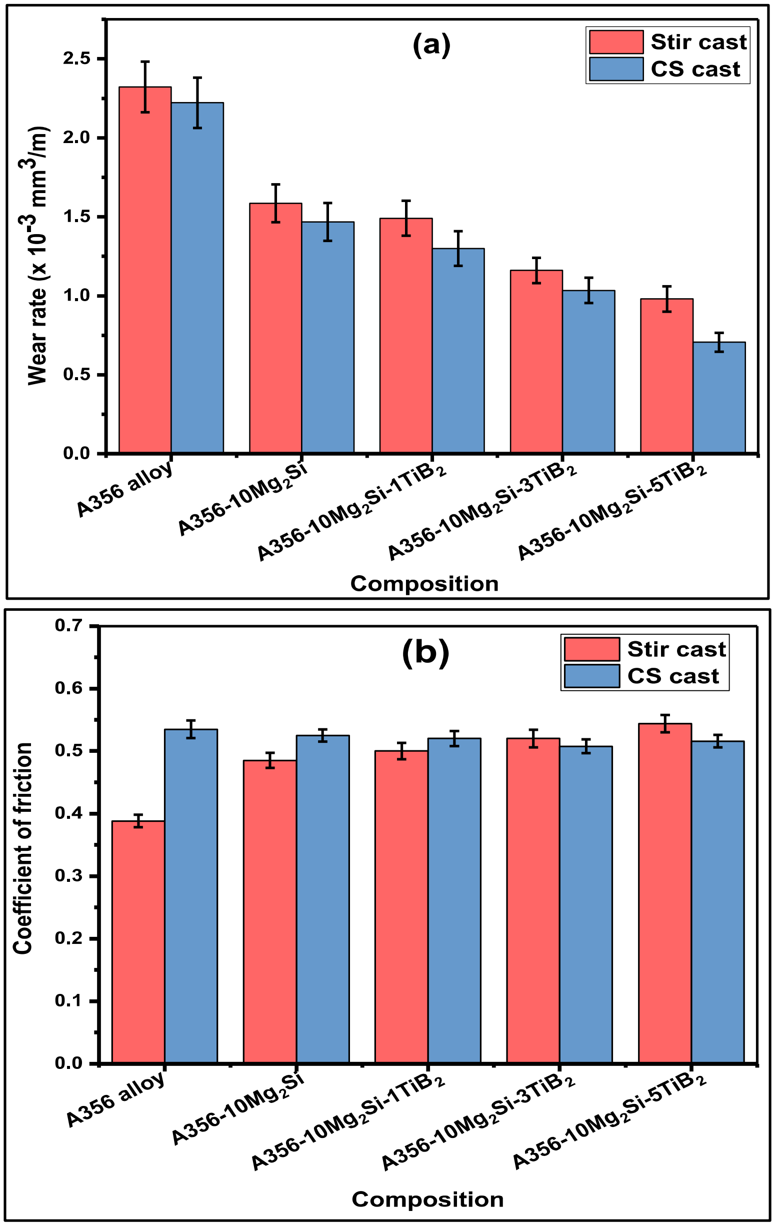

Fig. 6.22 Comparison of wear rate and COF of stir cast and CS cast base alloy and composites at fixed load, sliding distance and velocity

6.4 Summary

The influence of cooling slope casting on wear behaviour of $A356\text{-}10Mg_2Si\text{-}TiB_2$ in situ hybrid composites has been studied in this chapter. The following conclusions may be established based on the experimental results:

- Application of CS casting technique refines the grain size of matrix, reinforcement phase and distributed evenly, which increased the hardness and as a consequence wear behaviour of hybrid composites is improved.
- The CS cast hybrid composites have better load carrying capacity and the capability to maintain a protective stable oxide layer that protects the metal-to-metal contact during sliding wear.
- Wear rate of hybrid composite linearly increases up to 30 N and beyond that steady state wear regime is achieved at higher sliding distance. Whereas, COF of hybrid composites either stabilize or achieves decreasing trend at higher sliding distance at all loads.
- Wear rate of hybrid composite having 5wt.% TiB_2 shows 68.2% and 52% less wear compared with A356 alloy and $A356\text{-}10Mg_2Si$ composite respectively.
- COF of hybrid composites decreases with increasing amount of TiB_2 particles up to 3wt.% due to the lower surface contact. However, further increase of TiB_2 content, amount of the particles in the MML increases COF owing to abrasive action of the particles.
- CS cast hybrid composite having 5wt.% TiB_2 particles shows about 28.3% less wear rate compared with stir cast hybrid composites.
- Worn surface analysis shows that abrasive wear is dominant wear mechanism at low applied load and sliding distance while plastic deformation and delamination is dominant wear mechanism at higher load and sliding distance.

- AFM images of worn surface are also in agreement with the obtained results.